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AUG 79 M R MARTINELLI, S W MAYER, C C BADCOCK F04701-78-C-0079

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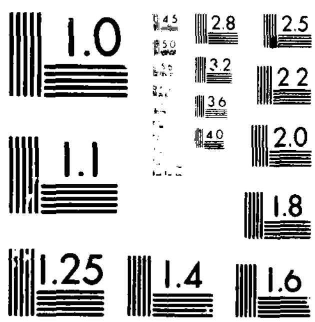

REPORT SAMSO-TR-79-93

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Phase Meter Measurement of State of Charge for Satellite NiCd Cells: A Preliminary Study

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Interim Report

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This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experiments were performed to determine if the phase angle between alternating voltage and current could be used to predict, within a probable error of 5%, the state of charge of seven individual sealed (General Electric) model 10AB08 NiCd) cells and a battery consisting of the seven cells in series. The cells were charged for various lengths of time at 0.8 A to obtain a range of state of charge; their phase angles were measured with a Hewlett-Packard HP3575A gain-phase meter at 35 Hz; and they were discharged at 5 A to 0.1 V to determine their state of charge in ampere-hours of capacity. The

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20. ABSTRACT (Continued)

phase angle state-of-charge data were subjected to second-order polynomial curve fitting by means of least-squares analysis. The probable errors obtained from the least-squares analysis were used to judge the quality of the measured correlation between phase angle and state of charge. In order to determine how the correlation might be affected through cell use, the four extensively cycled cells with more than 3700 charge-discharge cycles and three cells with less than 40 such cycles were tested. The effect of temperature on the correlation was also studied.

The goal of achieving a correlation between phase angle and state of charge with a probable error of 5% was reached for three of the seven cells and for the battery consisting of seven cells in series. Important differences between the extensively cycled and relatively uncycled cells were observed, however, as well as a strong temperature effect.

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I. INTRODUCTION

The development of a method for measuring satellite NiCd battery state of charge has been recognized as a technical need by the Air Force for more than ten years. Such a capability would improve on-orbit state-of-health monitoring of power systems, assist in precise load allocation, and provide direct capacity monitoring. Seiger et al.[1] have reviewed state-of-charge monitoring efforts, and presented an exceedingly restrictive set of conditions that a state-of-charge monitor must meet. Many of these conditions can possibly be relaxed if sufficient data are available and automatic computational capability is used. Impedance determinations were rejected earlier as a state-of-charge monitor,[1] but the development of improved equipment during the past few years warrants a reexamination of this method. The results of a study of phase angle as a monitor of state of charge are reported.

Latner[2,3] found a dependable correlation between the state of charge of sealed 0.5 A-hr NiCd cells and the electrical capacitance. We confirmed this correlation with the use of a Wayne-Kerr transformer ratio-arm bridge on 0.5 A-hr sealed NiCd cells. The correlation between capacitance and state of charge was within a probable error of 5% for individual cells and for up to 18 cells in a battery. This approach was not suitable for cells used on typical satellites because the capacitance (~20 F) exceeded the range of commercially available bridges. Consequently, the dependence of the phase angle on the state of charge was examined.

The phase angle between sinusoidal voltage and current for a NiCd cell has been previously evaluated as a state of charge indicator, with inconclusive results.[1,4] Advances in instrumentation, however, made it possible to obtain more precise measurements of phase angles (less than ±0.02 deg) than have been reported in past work on NiCd batteries. Results of preliminary work by Dowgiallo[*,5] in 1974 with the use of a Hewlett-Packard HP 3575A gain-phase meter indicated that the phase-angle method held promise as a reliable state-of-charge indicator for NiCd cells. Moreover, the phase angle of a cell is a function of the cell's capacitance, which Dr. Latner and the authors found to vary with state of charge.

Given the commonly used equivalent circuit for a battery (Fig. 1), where R_1 is the resistance of the cell terminal leads, L is the inductance of the cell terminal leads, R_s is the electrolyte resistance, and C is the capacitance of the cell, one can obtain the phase angle θ of such a circuit by using the equation

$$\theta = \text{Arctan}\ \frac{X_1(X_c^2 + R_s^2) + R_s^2 X_c}{R_1(X_c^2 + R_s^2) + R_s X_c^2}$$

where

$$X_c = \frac{1}{2\pi f C}$$

$$X_1 = 2\pi f L$$

f = frequency (Hz)

A preliminary study of the correlation between phase angle and state of charge was performed. The objectives were to determine if the state of charge could be predicted within a probable error of 5% and to briefly examine the effect of temperature (32 F and 92 F) on the correlation.

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[*] E. J. Dowgiallo and R. B. Anderson, Electrical Phase Measurements and State of Charge Indication, Presented at Fall 1974 Meeting of the Electrochemical Society, New York.

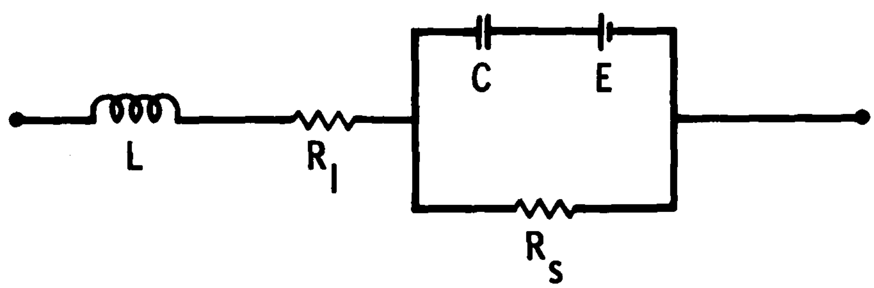

Figure 1. Battery Equivalent Circuit

II. EXPERIMENTAL PROCEDURE

Seven General Electric 10 A-hr sealed NiCd cells (model 10AB08) of the type used in satellites were obtained from Hughes Aircraft Corporation (HAC). Cells 1 and 2 had undergone 3998 charge-discharge cycles in an accelerated life test. Cells 3 and 4 had been subjected to 3732 cycles. Cells 5, 6, and 7 were relatively unused, having undergone only 30 cycles each during cell acceptance tests, but Cell 5 had failed a shorting test. All of the cells were from the same manufacturing lot.

Because the cells arrived in a completely discharged and shorted state, they required reconditioning before the state-of-charge research could be initiated. This was accomplished by taking the cells through a series of four charge-discharge cycles following a program similar to the procedure used at HAC for cell reconditioning. In each of these cycles, the cells were discharged at 5 A to 1 V then further discharged for 12 hr with a 1-ohm, 5-W resistor. In the first cycle, the cells were charged at 0.5 A. In the second cycle, they were charged at 1 A for 16 hr, and in the third and fourth cycle, they were charged at 1 A for 30 min past their peak voltage.

After the seven cells were reconditioned, 17 sets of phase angle versus state-of-charge measurements were made on each cell and on the battery formed by all seven cells in series. The cells were charged at 0.8 A, a rate used for many satellite batteries. The state of charge was set by varying the charging times from a few hours to 20 hr. Cell charging was generally begun automatically during the night through the use of a clock-timer switch. Immediately after charging was discontinued, the phase-angle shift readings were unsteady, probably because of thermal and concentration gradient changes arising from electrode polarization effects.[2] The measurement of the phase angles was consequently begun (as described below) three hours after charging was stopped. The state of charge for each of the seven cells was then determined by measuring the time required for discharging each cell to 0.1 V at 5 A. The 17 sets of measurements were made at room temperature, 73 ± 1 F, in an air-conditioned laboratory. The phase angle of the cells was measured using the circuit shown in Fig. 2. The Hewlett-Packard HP 3575A gain-phase meter was used to measure the phase angle between the ac voltage developed across the cell being monitored and the 8-ohm reference resistor. Lead impedance effects were reduced by monitoring the cells with a four-lead arrangement in which the ac current-carrying leads were separated from the voltage measuring leads. A quadruple pole, eight-throw, high-watt switch was used to transfer the four-lead arrangement to each of the seven cells and to measure all seven in series. The ac signal was provided by a Hewlett-Packard HP 204 oscillator and was amplified by a McIntosh 75 power amplifier to produce a current of 1.5 to 2 A rms in the circuit. At this amperage the signal developed across the battery is sufficiently large to be detected by the gain-phase meter without amplification. The 2000 μF blocking capacitor was used to prevent the cells from discharging through the amplifier. Although the 17 sets of measurements were made at ac signal frequencies of 35, 350 and 1000 Hz, the best results were obtained at the lowest frequencies. For this reason, only the 35 Hz results are reported here.

A Hewlett-Packard HP 6267B dc power supply was used to charge the cells and to maintain a constant current during their discharge. An Associated Testing BK-1100 environmental chamber was used to maintain the cells at a constant temperature during the 32 and 92 F runs.

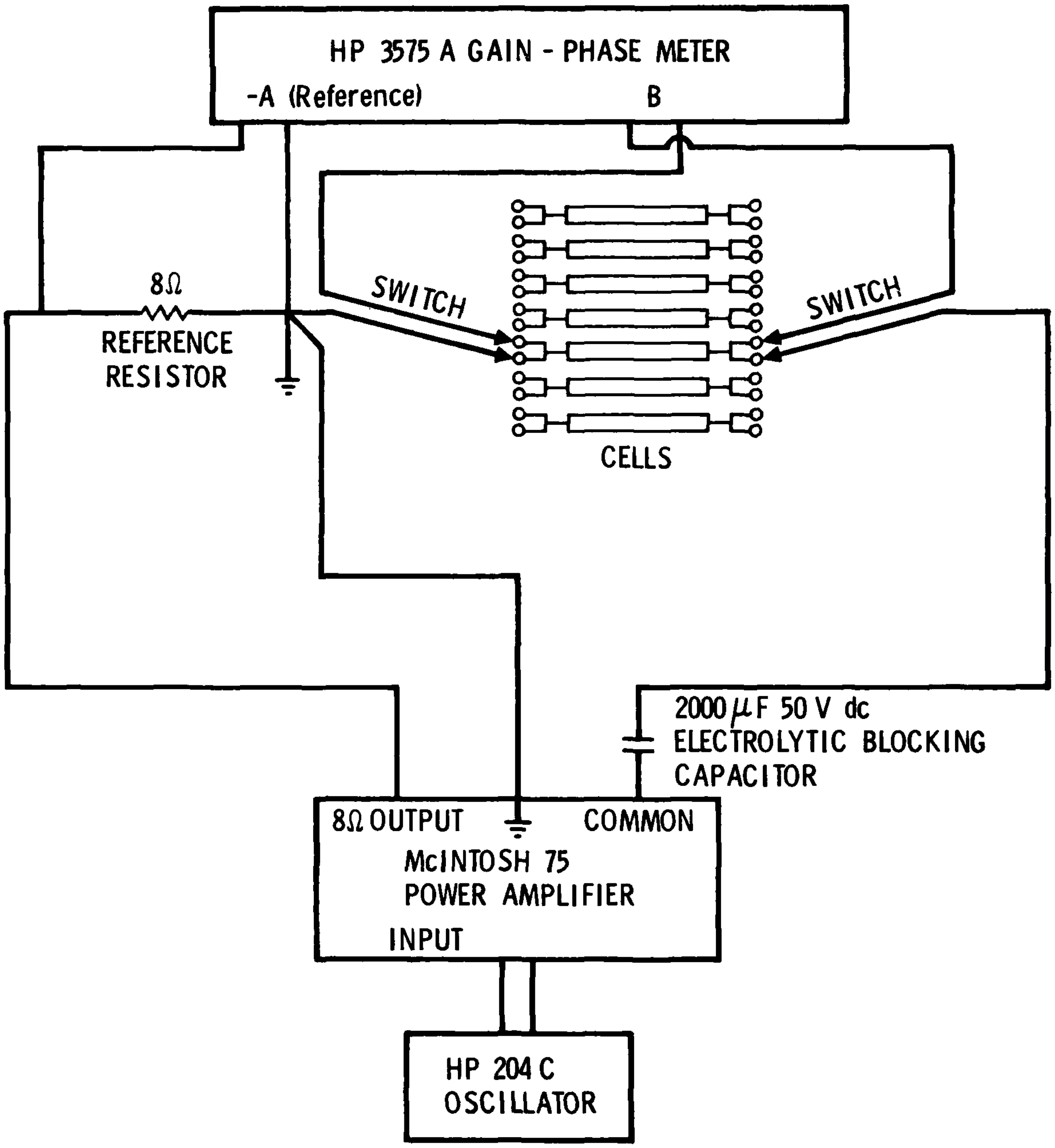

Figure 2. Phase Angle Measurement Circuit

III. RESULTS AND DISCUSSION

Plots of phase-angle readings versus ampere-hours of charge S for each cell and the battery of all seven cells in series are shown in the Appendix figures. Also shown in each figure is the curve fitted to the data with the use of least-squares analysis computed on the basis of the second-order power series: $S = a + b\theta + c\theta^2$. Along with fitting curves to the data, least-squares analysis allows computation of the standard deviation of data points from their corresponding curves and the probable error of the fit. These computations provide a measure of the quality of the curve fitting and a means by which to judge the quality of the measured correlation between phase angle and state of charge. The second-order power series gave the best and least ambiguous results. The results from first-order fits showed poorer correlations of θ to S whereas fitting the data to third- and fourth-order power series did not significantly improve the measured probable errors. A summary of the standard deviations and probable errors is presented in Table 1.

Table 1. State-of-Charge Standard Deviations and Probable Errors Determined from Second-Order Least-Squares Analyses (all data used)

Cell No.	Capacity, A-hr	Standard Deviation, A-hr	Probable Error, A-hr	Probable Error vs Capacity, %
1	12.2	0.34	0.23	1.9
2	11.9	0.27	0.18	1.5
3	12.8	1.07	0.72	5.6
4	12.3	0.64	0.43	3.5
5	13.1	1.76	1.19	9.1
6	12.7	1.53	1.03	8.1
7	12.7	1.36	0.92	7.2
Battery[a]	11.7	0.63	0.42	3.6

[a] All seven cells in series

Some cells exhibited excellent correlation between state of charge and phase angle, whereas the correlation for other cells was not very good. Cells 1, 2, and 4, for example, all showed correlations of θ to S with probable errors lower than the stated goal of 5%, whereas for Cell 5 the probable error was over 9%. It is also evident from the data in Table 1 that the correlation between θ and S was better for the extensively cycled cells (1, 2, 3, and 4) than for the relatively uncycled cells (5, 6, and 7). The average probable error for the extensively cycled cells was 0.39 A-hr, and for the relatively uncycled cells was 1.05 A-hr. These two groups of cells also differ in that throughout the entire range of state of charge, the cycled cells have lower (more capacitive) phase angles than the uncycled cells, and the average slopes ($\Delta S/\Delta\theta$) of curves for the cycled cell are less than those for the uncycled cells. These differences are evident in Table 2, in which the phase angle of each cell is given at the 7 A-hr capacity points (~60% fully charged) according to the second-order least-squares curve fit and the slope of the line obtained in a first-order least-squares analysis.

Table 2. Calculated θ at the 7 A-hr Capacity Point and Average Slopes of $\Delta S/\Delta\theta$ (all data used)

Cell No.	θ at 7 A-hr, deg	$\Delta S/\Delta\theta$ A-hr/deg	
1	-4.45	2.43	Extensively Cycled Cells
2	-4.09	2.22	
3	-4.26	3.27	
4	-4.33	3.38	
5	0.11	4.16	Relatively Uncycled Cells
6	0.45	6.07	
7	0.22	7.92	
Battery	-1.13	8.04	

It was noted that the correlation of θ with S seemed to improve for some cells during the course of the experiment. If the data from the first six measurements taken are discarded and least-squares analysis is performed, only on the last 11 points measured for each cell, the probable errors measured show marked improvement. A summary of the second-order least-squares analysis on the last 11 points for each cell is given in Table 3, and in each of the figures in the Appendix, the last 11 points measured are circled. Also included in Table 3 are the calculations of θ at the 7 A-hr capacity and the slopes of the first-order fits to the last 11 measurements for each cell. All the differences observed between the extensively cycled and relatively uncycled cells, with the use of all the data, were evident in the last 11 measurements as well.

The experiments designed to examine the effect of temperature on the measured correlation of θ to S involved modifying the measuring circuit by placing longer leads onto the cells so that they could be monitored while

Table 3. Summary of Results on Last 11 Measurements Taken on Each Cell

Cell No.	Standard Deviation, A-hr	Probable Error, A-hr	Probable Error, %	θ at 7 A-hr Capacity, deg	$\Delta S/\Delta\theta$, A-hr/deg	
1	0.16	0.11	0.9	-4.49	2.40	Extensively Cycled Cells
2	0.21	0.14	1.2	-4.08	2.19	
3	0.27	0.18	1.4	-4.39	3.57	
4	0.32	0.22	1.8	-4.45	3.29	
5	1.13	0.76	5.8	0.38	9.15	Relatively Uncycled Cells
6	1.18	0.80	6.3	0.62	8.55	
7	1.17	0.79	6.2	0.32	9.97	
Battery	0.38	0.26	2.2	-1.13	8.27	

inside an environmental chamber. Since the inductance of the leads affects the observed phase angles of the cells, the phase angles measured with the modified circuit cannot be directly compared to those taken with the original circuit. The relationship of θ to S was examined with the modified circuit at 32 and 92 F, and the results of these experiments are summarized in Table 4. During the experiment performed at 92 F, Cell 3 ruptured and did not yield meaningful results. Consequently, the results obtained with the battery consisting of all seven cells in series were voided for that experiment. As can be seen in Table 4, the phase angles of the cells vary directly in relation to temperature. By comparing the calculated values of θ at 7 A-hr at the two temperatures, one obtains an average dependence of $\sim +0.03°/°F$ for all the cells. Temperature correction would be necessary in many cases because the total change in θ from 100% to 40% charged is as small as one degree. The observed capacities of the cells were lower at 32 and 92 F than at 73 F; the extensively cycled cells showed a greater loss in capacity than the relatively uncycled cells. The correlation between θ and S also varied with temperature. Cells 1 and 2, which had the lowest

Table 4. Summary of Temperature Effect Experiments

Cell No.	Highest Observed Capacity	Probable Error, A-hr	θ at 7 A-hr, deg	Highest Observed Capacity	Probable Error, A-hr	θ at 7 A-hr, deg
	32 F			92 F		
1	7.75	0.91	-2.60	7.29	0.45	+0.03
2	7.55	0.74	-2.63[a]	7.70	0.45	-1.60[a]
3	8.14	0.71	-2.84			
4	7.14	0.54	-2.56	5.92	0.31	0.22
5	11.80	0.42	-0.42	9.87	0.32	1.03
6	11.27	0.61	-0.24	9.53	0.34	1.30
7	11.43	0.62	-0.27	8.99	0.23	1.11
Battery	9.14	1.04	-0.52			

[a]Cell 2 θ was calculated at 6 A-hr because the least-squares equation had a full charge value of less than 7 A-hr for 32 F.

probable errors at 73 F, yielded the poorest results at 32 and 92 F. The relatively uncycled cells (5, 6, and 7) exhibited better correlations of θ to S at 32 F and 92 F than they did at 73 F. The probable errors for Cells 3 and 4, on the other hand, showed only a slight change with temperature variation.

IV. CONCLUSIONS

The principal conclusion that can be drawn from this study is that phase-angle readings can be reliable state-of-charge indicators for NiCd cells under some conditions. It is not yet understood why the correlation between θ and S is better for some NiCd cells than for others. The goal of achieving a correlation between θ and S with a probable error of 5% was reached for three of the seven cells and for the battery made up of seven cells in series. When considering only the last eleven measurements taken on each cell, four individual cells and the seven-celled battery achieved the 5% probable error goal; the highest probable error attained was only 6.3%. Moreover, if one applies the standard statistical procedure of deleting points greater than two standard deviations from the least-squares curve, all of the cells meet the stated goal.

Other findings in this study, however, indicate that the phase-angle measurement technique does impose certain practical limitations. The three-hour delay before stable readings can be made, for example, could be a problem if immediate or continuous monitoring of state of charge is desired. Continuous, closed-circuit measurements were not attempted in this study. The 1.5 to 2 A rms ac measurement signal might be too severe a power commitment for some uses. Improvements in sensing circuit design, however, could eliminate this problem. A more serious problem indicated by the results of this study is that the relationship of θ to S is a function of the cell's history. This is most strikingly apparent when the results of the relatively uncycled cells are compared with those of the extensively cycled cells. From this comparison, it can be concluded that, as a cell is cycled, the relationship between θ and S should improve (both in terms of a lower probable error for the correlation and in terms of having a greater change in θ over the range of S); and the value of a measured phase angle for a given state of charge should become more negative (capacitive). This would require that the relationship between θ and S be reevaluated periodically for the method to be applicable throughout a cell's life. Moreover, short-term conditioning also has a significant effect on the relationship of θ to S as the results obtained from the least-square analysis of the last 11 measurements for each cell indicated. Finally, the study results indicate that there is a definite temperature effect on the correlation between θ and S that must be considered.

The method of evaluating the correlation of θ to S based on comparing the statistical probable errors should be clarified. The probable error of a fit merely indicates that a data point is as likely to be found within that error of the curve fit as without. The points that fell furthest from the θ versus S regression line for all data and for the last 11 points are listed in Table 5. When all data are used, the worst errors can be quite large, with four of the individual cells considered showing errors greater than 20% of their capacities. In the last 11 measurements, considerable improvement was noted for

Table 5. State-of-Charge Measurements Worst Deviations from Second-Order Curve Fits

Cell No.	All Data		Last 11 Measurements		
	A-hr	% of Capacity	A-hr	% of Capacity	
1	1.11	9.1	0.39	3.2	Extensively Cycled Cells
2	0.42	3.5	0.36	3.0	
3	3.26	25.5	0.45	3.5	
4	1.82	14.8	0.67	5.4	
5	3.60	27.5	2.18	16.6	Relatively Uncycled Cells
6	2.84	22.4	1.91	15.0	
7	2.70	21.3	1.91	15.0	
Battery	1.58	13.5	0.68	5.8	

the extensively cycled cells and the battery; all showed a worst-case error of less than 6%. The relatively uncycled cells, however, still have fairly large errors (approximately 15%) for these measurements.

In spite of all the shortcomings of this method, some cells performed very well. For example, Cell 2 showed a worst-case error of only 3.5% when all data were used. Another encouraging aspect of the results is that the errors for the battery composed of all seven cells in series are generally quite good and always better than the averaged errors of the individual cells (although the average value of $\Delta S/\Delta\theta$ for the battery is high). Because NiCd batteries are used more often than individual cells, the success of a state-of-charge indicator for a battery is of greater significance. Additionally, one might expect even better results from a battery composed of more closely matched cells, all with good θ to S correlations.

Although no specific recommendations can be made on the basis of the results of this study, there appear to be some circumstances where the phase-angle method of state-of-charge determination could prove valuable.

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APPENDIX

Figures A-1 through A-8 show the phase angle (in degrees) versus state-of-charge (in ampere-hours of capacity) plots for cells 1 through 7 and the battery comprised of all seven cells in series. In each figure, the second-order least-squares curve fit to all 17 measurements taken is also shown. The last 11 measurements taken are circled in each figure.

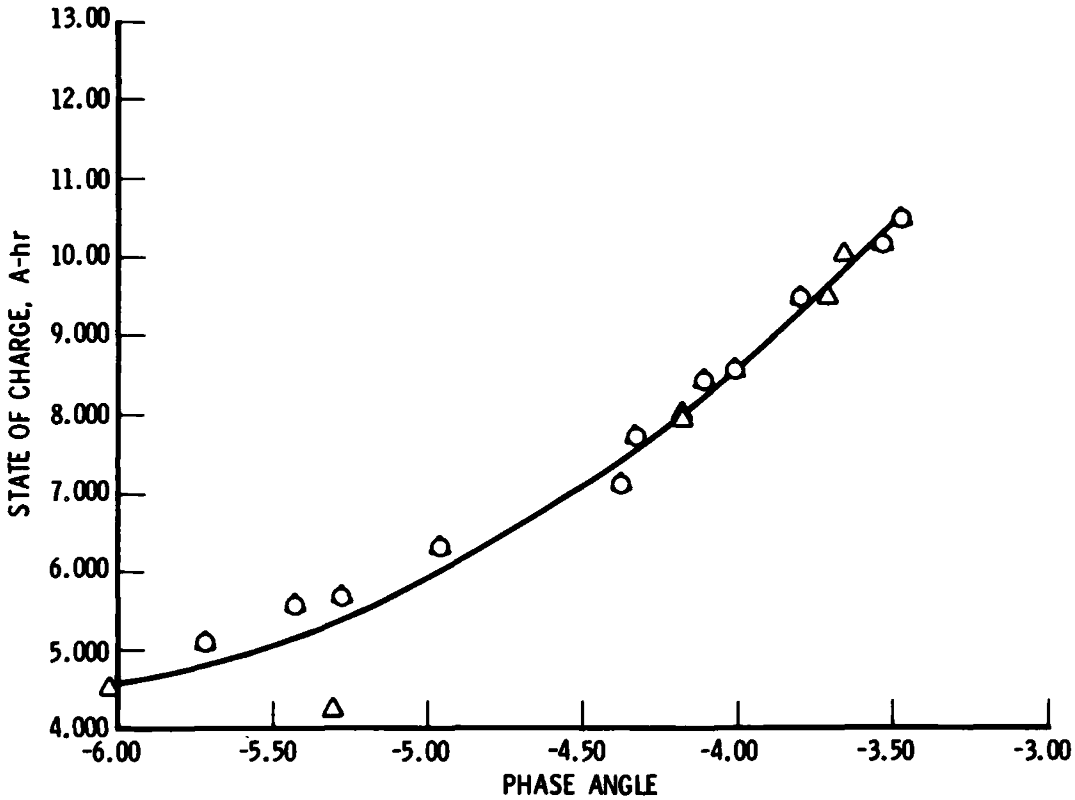

Figure A-1. Phase Angle vs State of Charge for Cell 1 at 35 Hz and Room Temperature

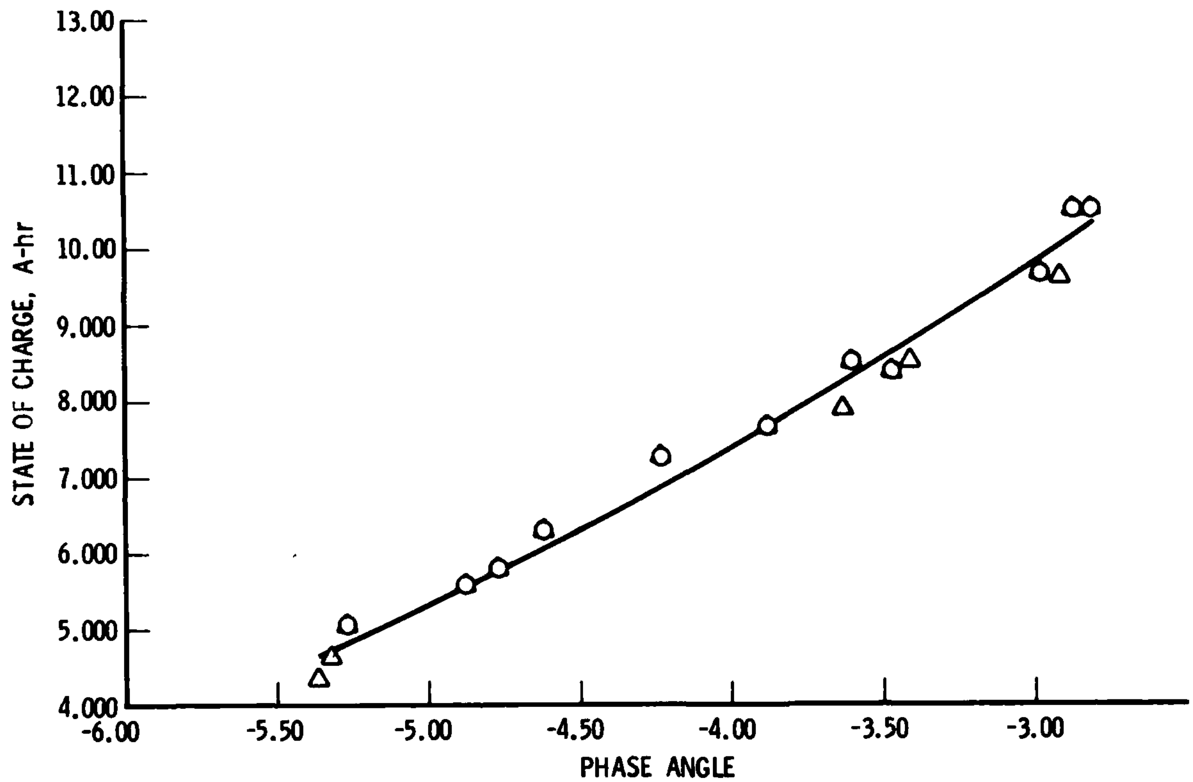

Figure A-2. Phase Angle vs State of Charge for Cell 2 at 35 Hz and Room Temperature

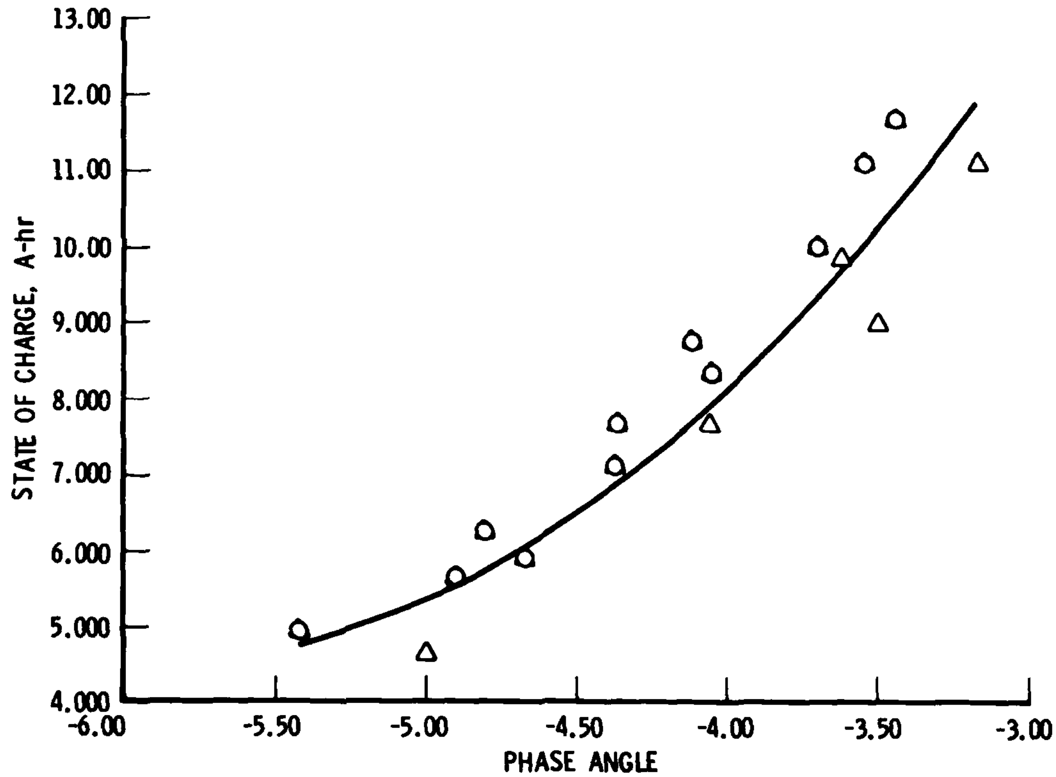

Figure A-3. Phase Angle vs State of Charge for Cell 3 at 35 Hz and Room Temperature

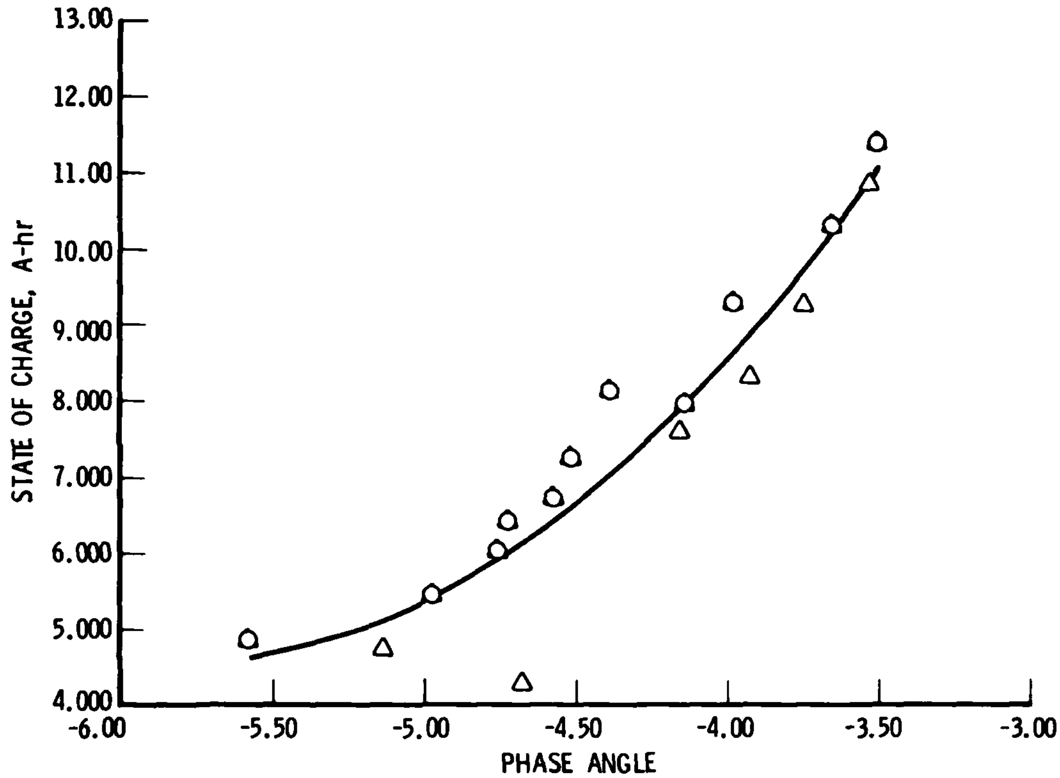

Figure A-4. Phase Angle vs State of Charge for Cell 4 at 35 Hz and Room Temperature

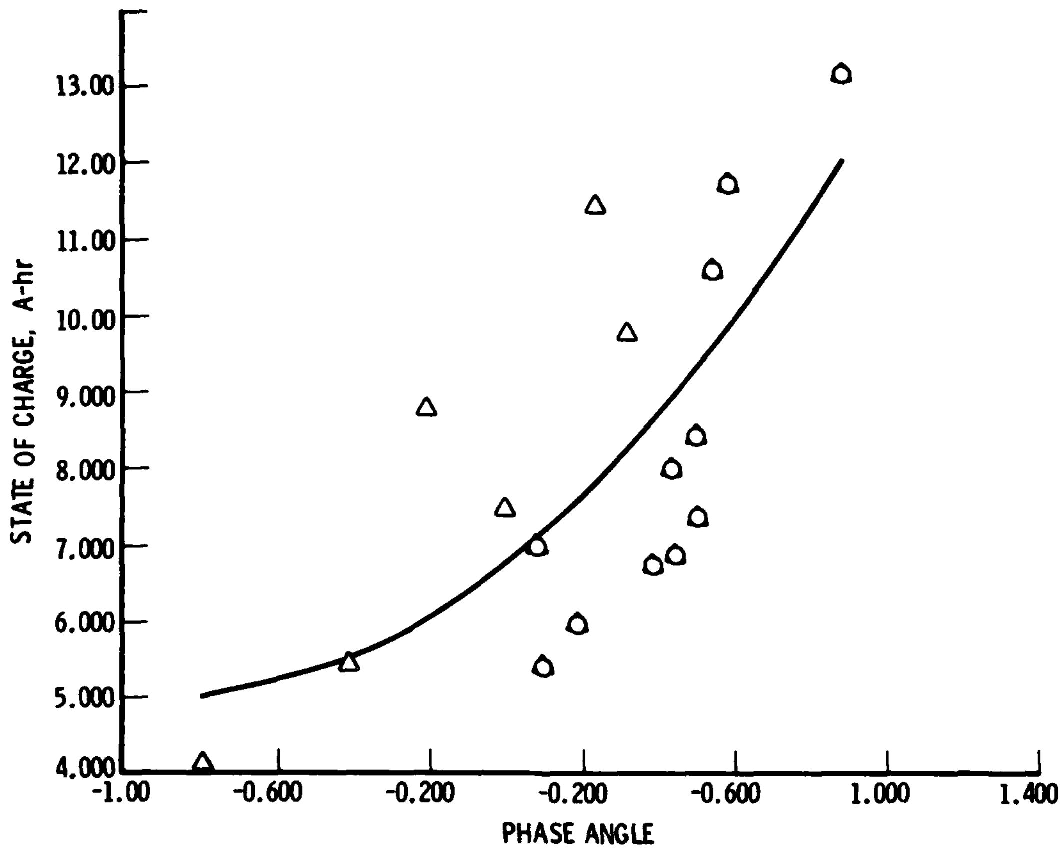

Figure A-5. Phase Angle vs State of Charge for Cell 5 at 35 Hz and Room Temperature

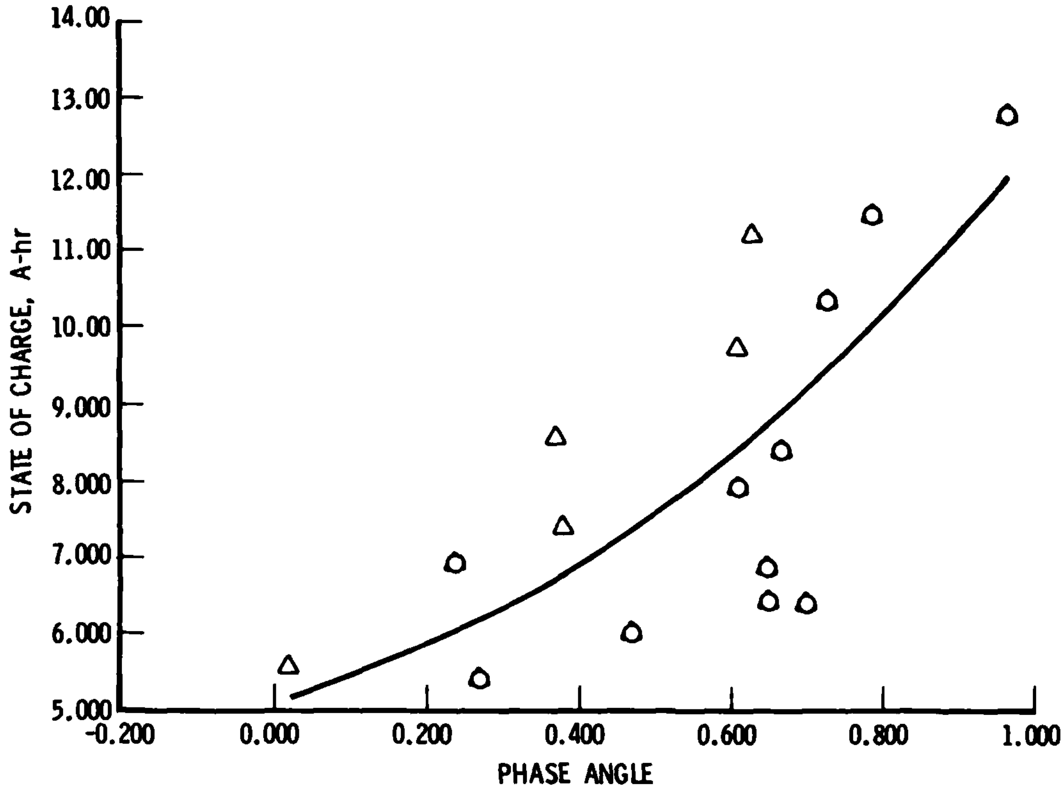

Figure A-6. Phase Angle vs State of Charge for Cell 6 at 35 Hz and Room Temperature

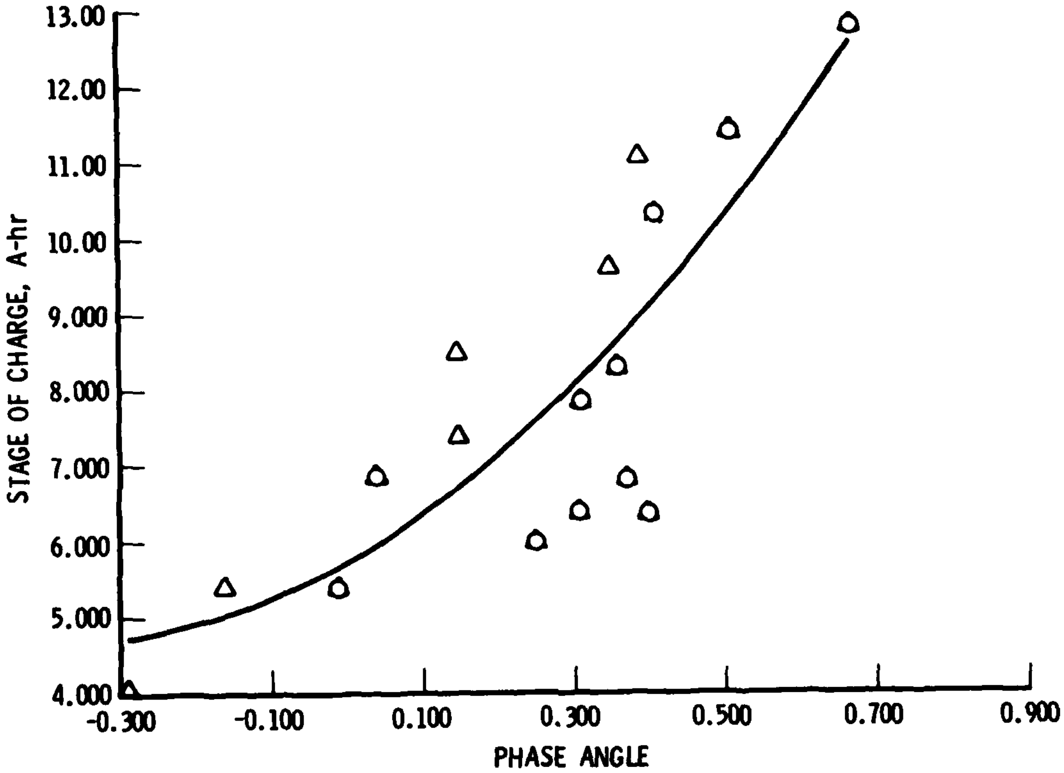

Figure A-7. Phase Angle vs State of Charge for Cell 7 at 35 Hz and Room Temperature

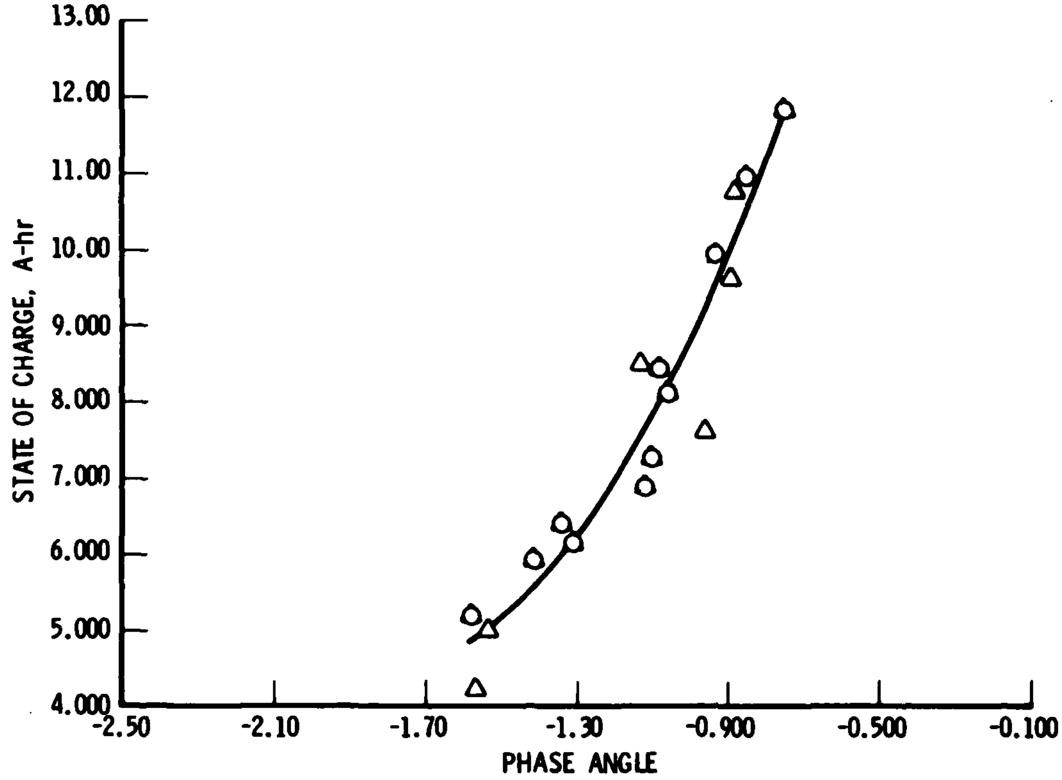

Figure A-8. Phase Angle vs State of Charge for the Battery Composed of Seven Cells in Series at 35 Hz and Room Temperature

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Aerophysics Laboratory: Launch and reentry aerodynamics, heat transfer, reentry physics, chemical kinetics, structural mechanics, flight dynamics, atmospheric pollution, and high-power gas lasers.

Chemistry and Physics Laboratory: Atmospheric reactions and atmospheric optics, chemical reactions in polluted atmospheres, chemical reactions of excited species in rocket plumes, chemical thermodynamics, plasma and laser-induced reactions, laser chemistry, propulsion chemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, photosensitive materials and sensors, high precision laser ranging, and the application of physics and chemistry to problems of law enforcement and biomedicine.

Electronics Research Laboratory: Electromagnetic theory, devices, and propagation phenomena, including plasma electromagnetics; quantum electronics, lasers, and electro-optics; communication sciences, applied electronics, semiconducting, superconducting, and crystal device physics, optical and acoustical imaging; atmospheric pollution; millimeter wave and far-infrared technology.

Materials Sciences Laboratory: Development of new materials; metal matrix composites and new forms of carbon; test and evaluation of graphite and ceramics in reentry; spacecraft materials and electronic components in nuclear weapons environment; application of fracture mechanics to stress corrosion and fatigue-induced fractures in structural metals.

Space Sciences Laboratory: Atmospheric and ionospheric physics, radiation from the atmosphere, density and composition of the atmosphere, aurorae and airglow; magnetospheric physics, cosmic rays, generation and propagation of plasma waves in the magnetosphere; solar physics, studies of solar magnetic fields; space astronomy, x-ray astronomy; the effects of nuclear explosions, magnetic storms, and solar activity on the earth's atmosphere, ionosphere, and magnetosphere; the effects of optical, electromagnetic, and particulate radiations in space on space systems.

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